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LETTER TO THE EDITOR

Intrinsic limits on carrier mobilities in double-layer systems

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Abstract. An expression for *intralayer* resistivity in a double-layer system due to Coulomb scattering between current carriers is derived. It is shown that Coulomb interlayer carrier–carrier interaction imposes limits on available mobilities *within* each layer. The limits become restrictive for small layer separations and low carrier concentrations when short-range Coulombic correlations significantly modify interactions in the system, in particular for electron–hole double layers at temperatures corresponding to the Fermi energy. In some cases these intrinsic limits for the mobilities may be as low as 3×10^4 cm^2 V^{-1} s^{-1} for a GaAs/GaAlAs/GaAs heterostructure system—possibly one of the reasons for low mobilities in multilayer systems.

Quasi-two-dimensional electron and electron–hole systems (single layer, multilayer, etc) have become prominent in recent years in condensed-matter physics both because of their technological importance and as a testing ground for many-body theories. The single most important reason for this is the very high carrier mobilities achievable in single-layer GaAs/GaAlAs heterostructure systems. High mobilities (i.e. low scattering rates) allow the observation of highly correlated electronic states, like the fractional quantum Hall effect in high magnetic fields [1] or the Wigner crystallization predicted for extremely low carrier concentrations [2]. Addition of a second layer with a potential barrier thick enough to prevent tunnelling [3] enhances, in principle, carrier–carrier correlations [4], possibly producing the Wigner crystallization at higher densities and leading to novel correlated ground states, like charge-density waves [5] and a superfluid state resulting from electron–hole attraction in double-layer electron–hole systems [6]. Experimentally, however, it is much more difficult to achieve very high mobilities in multilayer systems. It is important to ask whether the limits on mobilities in such systems are merely of technological nature or whether there exist more fundamental limits as well. We show in this article that recent developments in the understanding of transport in double layers [7–11] allow us to place important intrinsic limitations on mobilities.

Transport properties of multilayer systems are directly affected by carrier–carrier Coulomb interactions—in contrast to normal phases in single layers (in zero magnetic field) where these interactions affect transport only indirectly through the screening of potentials responsible for scattering. A good example is given by the interlayer Coulomb drag when electric current flowing in one layer of a double-layer system may drag along the carriers in the other layer. The drag force is due to the momentum and energy exchange between the layers mediated by elementary single-particle and collective excitations. To probe the interactions responsible for this effect one disallows the current flow in one of the layers; the resulting charge polarization produces an electrostatic field which compensates for the drag

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force. The ratio of the field to the current density in the drag layer, called the transresistivity, is a direct measure of the interactions responsible for the drag [7–11].

Mobilities in a single layer are affected by scattering of carriers due to imperfections or impurities. In the double-layer system, however, there is an additional interaction of carriers in one layer with those in the other one. The effective mobility in the first layer is directly affected by the carrier–carrier interlayer interaction and may be written as

$$\frac{1}{\mu_1^{\mathrm{eff}}} = \frac{1}{\mu_1^{\mathrm{s}}} + \frac{1}{\mu_1^{\mathrm{C}}} \tag{1}$$

where $1/\mu_1^{\mathrm{s}}$ and $1/\mu_1^{\mathrm{C}}$ are due to the presence of fixed scatterers (impurities, etc) and the presence of carriers in the second layer, respectively.

A notable implication of equation (1) is that the mobility in the drag layer is limited by the Coulomb interactions with the carriers in the second layer. As the quality of the sample improves and disorder scattering becomes less effective, the mobility measured in the lth layer increases until it reaches its highest possible value, μ_l^{C}, set up by the interlayer interactions. This limit depends on the concentration of carriers in both layers and also on the temperature of the sample.

Experimental separation of the interlayer Coulomb scattering contribution to the *intralayer* mobility is difficult. Intuitively, it should be related to the strength of the interlayer Coulomb drag which is much easier to measure. The first experiments on Coulomb drag were performed on electron–electron double-layer systems with relatively high concentrations of carriers [7]. The measured Coulomb drag was small, giving rise to a generally held opinion that the interlayer Coulomb scattering is always small, so the *intralayer* mobility is always dominated by impurity (or phonon, etc) scattering, i.e. that, practically, the interlayer Coulomb scattering does not impose limits on intralayer mobilities measured in real samples. However, recent experiments on electron–hole systems with low concentrations of carriers [8] show that correlations alone can boost Coulomb drag by an order of magnitude [11, 12]. Also, larger effective masses of holes and higher temperatures make interlayer Coulomb scattering more effective. Therefore, the question of whether the interlayer Coulomb-scattering-dominated regime of intralayer transport can be reached in real samples needs to be addressed.

Rather than deriving from first principles an expression for the intralayer mobility μ_1^{C} due to interlayer Coulomb scattering, we use simple physical arguments to relate it rigorously to the transresistivity which can be measured independently and has already been calculated theoretically [7–12]. If a current $\boldsymbol{j}_l$ flows in the lth layer of a double-layer system then a net friction force $\boldsymbol{F}_l^{\mathrm{fric}} = -(m_l/e_l\tau_l^{\mathrm{s}})\boldsymbol{j}_l$ acts on all charge carriers in it (electrons or holes with effective mass m_l and charge e_l) as a result of scattering, described by the effective relaxation time τ_l^{s}, due to disorder, impurities, imperfections, etc. All forces acting on the gas in the layer must balance in a steady state so, for $l = 1$, we get

$$n_1 e_1 \boldsymbol{E}_1 - \frac{m_1}{e_1\tau_1^{\mathrm{s}}}\boldsymbol{j}_1 + \boldsymbol{F}_{12}^{\mathrm{drag}} = 0 \tag{2}$$

where n_1 and $\boldsymbol{E}_1$ are, respectively, the carrier concentration and the electric field in this layer, and $\boldsymbol{F}_{12}^{\mathrm{drag}}$ is the drag force experienced by the gas in the first layer due to Coulombic interactions with the charge carriers in the second layer. Adding equation (2) to a similar equation for $l = 2$, using the third Newton's law: $\boldsymbol{F}_{12}^{\mathrm{drag}} = -\boldsymbol{F}_{21}^{\mathrm{drag}}$, employing the relations

$$\boldsymbol{E}_l = \sum_{l'=1}^{2} R_{ll'}\boldsymbol{j}_{l'} \tag{3}$$

where $R_{ll'} = R_{l'l}$ are the components of the resistivity of the double-layer system, and observing that currents can be set up independently in each layer, we obtain

$$R_{11} = \frac{1}{n_1 e \mu_1^{\mathrm{s}}} - \frac{n_2 e_2}{n_1 e_1} R_{21}. \tag{4}$$

Here, $e = |e_l|$ and $\mu_l^{\mathrm{s}} = e\tau_l^{\mathrm{s}}/m_l$ is the mobility in the lth layer due to the disorder scattering, i.e. the mobility measured in the isolated layer. The second term in equation (4) (taken with its sign) is always positive because, as seen from equation (3), R_{21} is positive for the electron–hole double-layer system and negative for the electron–electron system. A similar relation is obtained between R_{22} and R_{12}. In the usual experimental set-up the current is allowed to flow through one layer only, say $l = 1$ (termed the drag layer), while the other layer is stopped, i.e. $j_2 = 0$. Defining an *effective* carrier mobility in the drag layer in terms of its measured resistivity, $1/\mu_1^{\mathrm{eff}} = n_1 e R_{11}$, and the residual mobility due to the presence of carriers in the second layer:

$$\frac{1}{\mu_1^{\mathrm{C}}} = e n_2 |R_{21}| \tag{5}$$

one obtains equation (1) from equation (4).

Equation (4) relates the resistivity measured in each of the layers to the transresistivity R_{21} which can be measured independently [7, 8]. Theoretical expressions for R_{21} were derived repeatedly in the past using microscopic models [7–11]. We use here the expression which includes electron–electron correlations [11]. By substituting it into equation (4) we can write out *all* components of the resistivity:

$$R_{ll'} = \frac{1}{n_l e_l \mu_l^{\mathrm{s}}} \delta^{ll'} + (2\delta_{ll'} - 1) \left(\frac{\beta \hbar^2}{2 n_l n_{l'} e_l e_{l'}} \right) \times \frac{1}{\Omega} \sum_{\boldsymbol{q}} q^2 \int_{-\infty}^{\infty} \frac{\mathrm{d}\omega}{2\pi} \frac{\left(V_{12}^{\mathrm{eff}}(\boldsymbol{q}) \right)^2}{|\epsilon(\boldsymbol{q}, \omega)|^2} \frac{\operatorname{Im} \chi_1(\boldsymbol{q}, \omega) \operatorname{Im} \chi_2(\boldsymbol{q}, \omega)}{\cosh(\beta \hbar \omega) - 1}. \tag{6}$$

The microscopic derivation of both diagonal and off-diagonal components of $R_{ll'}$ based on a general linear response theory for two-component fermion systems [12] is consistent with the result given in equation (6). Here, $\beta = 1/k_B T$, $\chi_l(\boldsymbol{q}, \omega)$ is the Lindhardt susceptibility function for a two-dimensional gas in the lth layer, and $\epsilon(\boldsymbol{q}, \omega)$ is the dielectric function appropriate for the double-layer system [9–12, 15] which screens the effective Coulomb interaction $V_{12}^{\mathrm{eff}}(\boldsymbol{q})$ between the carriers on both sides of the potential barrier separating the layers. We are interested here in the intrinsic limit of mobility in the zero-disorder limit; therefore, the disorder is not included in the second term of equation (6), describing the Coulomb scattering contribution. Note that even in the finite-disorder case this is a good approximation, since although in samples experimentally investigated so far the first term is larger than the second term, the influence of disorder on the transresistivity is negligible [10, 11].

The dielectric function in equation (6) depends on both interlayer, $V_{12}^{\mathrm{eff}}(\boldsymbol{q})$, and intralayer, $V_{ll}^{\mathrm{eff}}(\boldsymbol{q})$, effective Coulomb interactions. Explicit expressions for the dielectric function and the effective interactions were given and their physical role was discussed in [11] where it was also shown that short-range Coulombic correlations are important in this problem since they can change R_{21} by almost an order of magnitude. The correlations are taken into account in all effective interactions through the static local field corrections calculated using the Singwi–Tosi–Land–Sjölander method [13] generalized for two-component plasmas [14] and double-layer systems in particular [15]. This approach has been extremely successful in

describing experimentally measured transresistance in electron–electron and electron–hole double-layer systems [11].

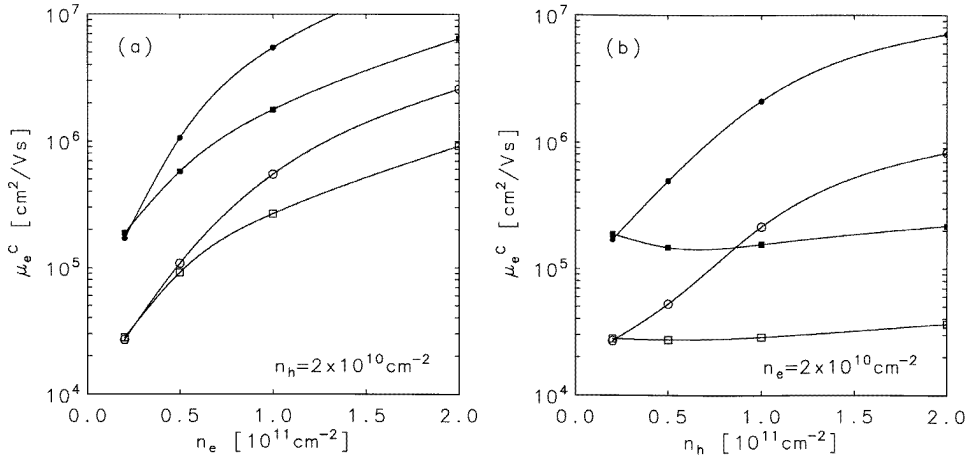

Figure 1. The electron (a) and hole (b) concentration dependence of the upper limit of electron mobility in the electron–hole double-layer system with a stopped hole layer. The thickness of each layer is $a = 100$ Å and the distance between their centres is $d = 150$ Å (open symbols) and $d = 300$ Å (full symbols). Temperatures: $T = 4$ K (circles) and $T = 40$ K (squares).

In figure 1 the concentration dependence of the upper mobility limits in the electron drag layer are shown for electron–hole double-layer systems for two temperatures and two values of the barrier width separating the gases and for the carrier concentrations typically available in these systems [8]. The calculations were done using equation (6) with disorder scattering set equal to zero. Similar graphs for the hole drag layer upper mobility limits in these systems can be obtained from the relation $\mu_h^C = (n_h/n_e)\mu_e^C$.

Two points are worth noting. First, the electron mobility limit due to the Coulomb drag increases with increasing electron concentration in the drag layer (figure 1(a)). Secondly, at lower temperatures, the mobility increases also with increasing concentration of carriers in the stopped layer (figure 1(b)), in contrast to the picture according to which they might act as individual 'scatterers' for the carriers in the drag layer. At a microscopic level, the interlayer scattering of the carriers in the drag layer is a many-body effect involving particle-density fluctuations in both layers. Thermally excited single-particle and collective excitations in the drag layer change their momentum and give up their energy by promoting similar excitations in the other layer by means of the across-the-barrier Coulomb interaction between the carriers. We note that, similarly to the transresistivity case [11], short-range Coulombic correlations significantly affect the results presented in figure 1. Without them the mobility limits would be higher by a factor of 5 to 10.

The lowest carrier concentrations used in the present calculations, 2×10^{10} cm^{-2}, correspond to the lowest experimental carrier densities in mobile electron–hole samples of [8]. At still lower concentrations in the stopped layer, say, the carriers in it may undergo a localization on defects and act as Coulomb scattering centres for the carriers in the drag layer. In such a case the theory leading to equation (6) no longer applies and the stopped layer concentration dependence of the upper mobility limit in the drag layer is different to that in figure 1(b).

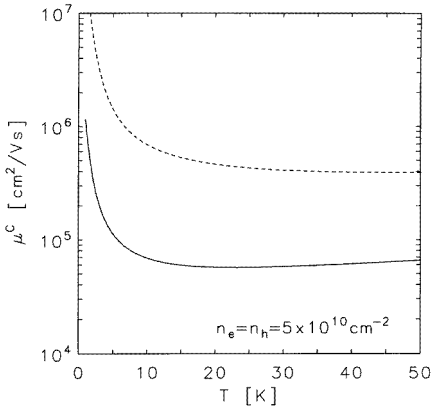

Figure 2. The temperature dependence of the upper limit for the carrier mobility in an electron–hole double-layer system for $d = 150$ Å (solid line) and 300 Å (dashed line).

The thermally activated nature of the scattering process is evident in the temperature dependence of the drag layer mobility limit seen in figure 2 for equal carrier concentrations in both layers (note that in this case $\mu_h^C = \mu_e^C \equiv \mu^C$). As $T \to 0$ the interlayer interactions do not impose any upper limit on the mobility (i.e. $\mu^C \to \infty$), because with no density fluctuations present both gases are uniform and cannot exchange energy or momentum. The upper mobility limit sets up quickly as the temperature increases above the hole Fermi temperature ($\approx$3.1 K in this example), reaches its minimum, and increases rather slowly with further temperature rise because above the Fermi temperatures of both subsystems all available elementary excitations are already contributing to the interlayer scattering.

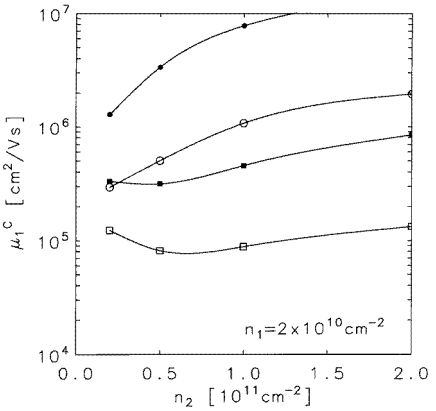

Figure 3. The stopped layer carrier concentration dependence of the upper limit for the electron mobility in the electron–electron double-layer system for $a = 100$ Å. Remaining parameters: $d = 165$ Å (open symbols); $d = 300$ Å (full symbols); $T = 4$ K (circles); $T = 40$ K (squares).

The drag layer ($l = 1$) upper mobility limit versus the concentration in the stopped layer ($l = 2$) in the electron–electron double-layer system is shown in figure 3. The effective mass of carriers filling both layers is the same, so the upper mobility limit dependence upon the carrier concentration in the drag layer (analogous to figure 1(a)) can be obtained by

multiplying the values in figure 3 by n_2/n_1 and then interchanging n_1 and n_2 in the graph. Comparison of figure 3 with figure 1(b) indicates that the mobility limitation due to the Coulomb drag is not as severe in the electron–electron double-layer system as it is in the electron–hole double-layer system. The main reason for this is the lower effective mass of electrons and less pronounced role played in the electron–electron system by the short-range Coulombic correlations in the across-the-barrier energy and momentum exchange [11].

In conclusion, we have examined the Coulomb carrier–carrier scattering in double-layer systems and found that it imposes upper limits on carrier mobilities in each layer. These limits are more severe in the electron–hole systems than they are in the electron–electron systems and are more important at low carrier concentrations and small layer separations. They might be one of the reasons for high-mobility double-layer samples being difficult to obtain.

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